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Low carbon construction using *Guadua* bamboo in Colombia

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Abstract. *Guadua Angustifolia Kunth* (*Guadua*) is a tropical species of bamboo endemic to South and Central America and widely used as a mainstream material for construction in Colombia. Its rapid rate of biomass production, renewability, high level of CO₂ fixation and storage, wide diameter, long-length, and durability are distinctive and highly desirable features which can benefit the new built environment

Research interest in *Guadua* construction increased significantly after many *Guadua*-constructed buildings withstood or suffered only minor damage during an earthquake which reached 6.2 on the Richter scale in 1999, resulting in the standardization of *Guadua* in the seismic-resistant Colombian code (NSR, 2010). However, *Guadua* buildings constructed in the Americas and other parts of the world, whilst considered to be sustainable, are not fully characterised in terms of the preparation, use and disposal of *Guadua*. Furthermore, workability, building durability and the construction process have not been specifically documented and evaluated.

The structure, properties and availability of *Guadua* are described in this paper. A case study on a recently built holiday house is presented illustrating the architectural, structural, environmental and technical performance of a *Guadua* building. This paper presents the construction process, discusses difficulties encountered during the building life cycle and highlights the need for similar assessments. It is concluded that with the aim of achieving a low carbon construction system using *Guadua* bamboo, challenges regarding manufacture, bio-deterioration, integration with conventional systems, and environmental impacts must be addressed.

Introduction

Bamboo

Commonly referred to as a giant grass, bamboo is an Angiosperm plant from the Poaceae –Gramineae family (grasses) which propagates rapidly by the expansion of underground rhizomes. Unlike trees, bamboos have only one growth stage where the culm (stem) seen in Figure 1a reaches its full height, diameter and wall thickness during the first four to six months of life. Subsequently, consolidation of tissue occurs by secondary thickening until maturity. The fast elongation of its culm is a result of the simple structure of fibres, conductive tissue and parenchyma units (Figure 1b) arranged axially along the stem which allows cellular differentiation and rapid flow of nutrients. As shown in Figure 1a, the continuity of the culm is interrupted by diaphragms that transversely connect the vascular system. The cortex (outer part) is rapidly consolidated with a high content of lignin and silica, providing protection for the load bearing tissue during growth. No growth occurs in the radial, longitudinal or tangential direction in the following years.

Depending on its rhizome structure, tropical and temperate bamboos are classified as sympodial and monopodial. Both present distinctive anatomical and morphological features which determine their

physical and mechanical properties (density, strength, bending behaviour, shrinkage and splitting) and thus their end uses. Sympodial bamboos in tropical areas have been widely used in construction and monopodial bamboos in subtropical regions are mainly used for less demanding applications. For example, the sympodial species *Guadua Angustifolia Kunth* (guadua) grows in South and Central America and is suitable for construction. In contrast the monopodial *Phyllostachys heterocycla pubescens* (moso) is grown in Asia and is more suitable for parquet, furniture and decorative applications [1]. The worldwide distribution of bamboo is summarised in Figure 2.

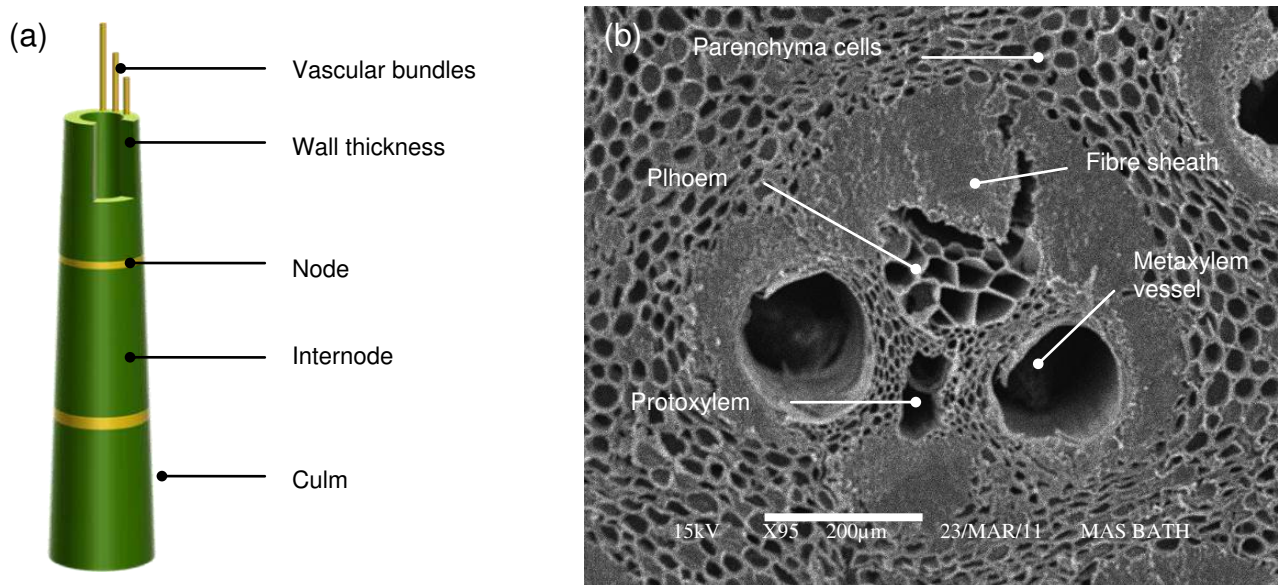


Figure 1 (a) bamboo culm, (b) vascular bundle (*Guadua Angustifolia Kunth*)

Bamboo resources have been recently listed as a Non Wood Forest Product (NWFP) and wood substitute at FAO's last Forest Resource Assessment [2]. From a total bamboo forest of about 1 % of the world's land area (31.5 million ha), moso covers about 70% of the total 3.7 million ha of bamboo forest in China [3], while guadua resources in Colombia account only for some 51.5 thousand ha [4].

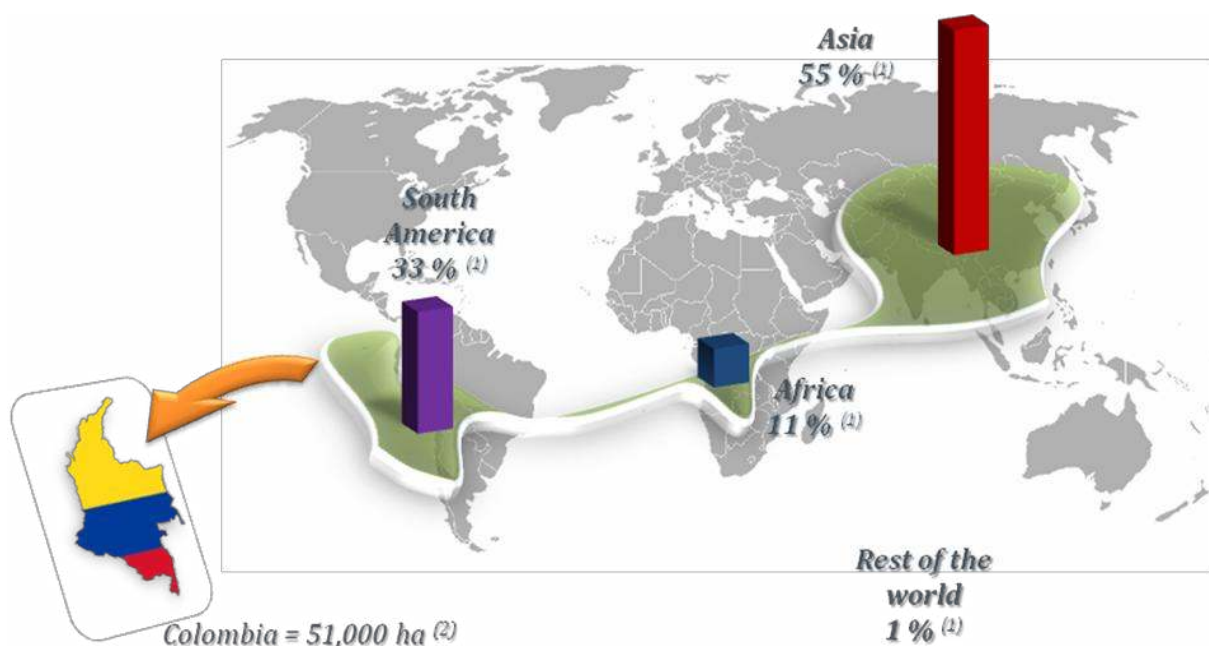


Figure 2. Worldwide distribution of bamboo. ¹ [2], ² [4].

Guadua

Guadua Angustifolia Kunth (Guadua) from the subtribe Guadinae is a tropical species of bamboo endemic to South America widely used as a mainstream material for construction in Colombia. It commonly grows at altitudes between 500 and 1500m, in the temperature range 18 to 24° C and relative humidity 80 to 90% in regions with precipitation varying from 1200mm to 2500mm per year [4]. This sympodial bamboo can grow at a maximum rate of 21cm per day to an average height of 25m in the first 6 months (Figure 3a). Its base diameter can reach 22cm, becoming mature between the fourth and fifth year (Figure 3b). These features, along with a specific gravity between 0.7 and 0.8, high strength-to-weight ratio, higher durability than other bamboos, ease of use, abundance and low cost, has contributed to its use in construction applications in Colombia.

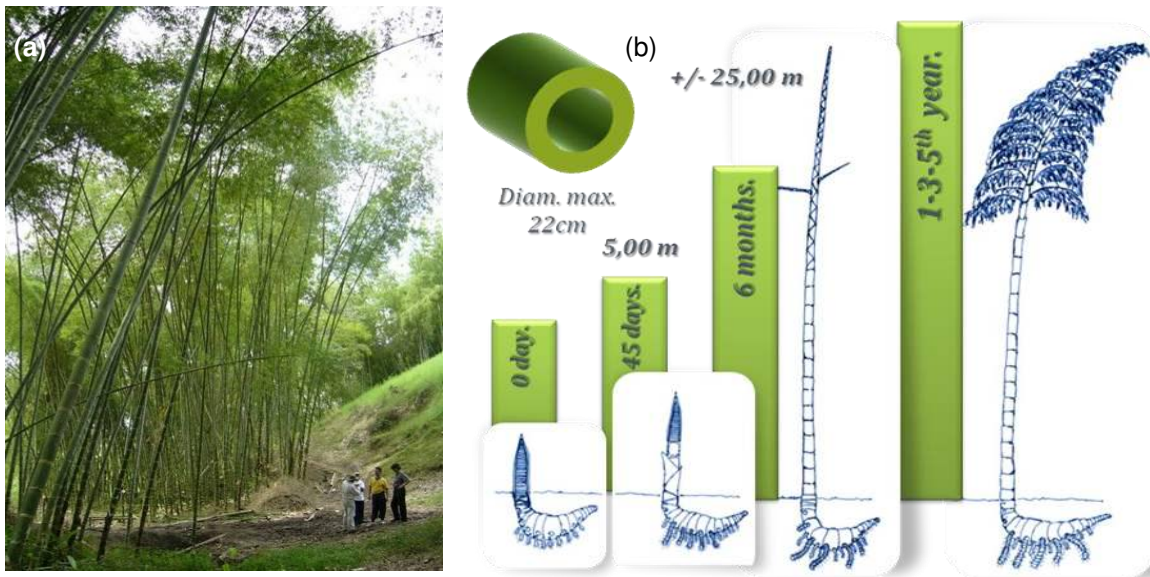


Figure 3 (a) Guadua plantation in Colombia, (b) Growth of Guadua culm

Guadua's structural integrity was dramatically tested in 1999 in Colombia during an earthquake (6.2 on the Richter scale) that devastated a vast area of the coffee growing region (zona cafetera). Most of the buildings built out of Guadua survived with minor structural damage whilst conventional concrete buildings collapsed and almost 60% of all buildings fell down. Since this episode, interest in research on the mechanical response of Guadua and its suitability for construction has resulted in its standardization in the seismic-resistant Colombian code (NSR-10) for (a) dwellings of one and two stories and (b) residential, commercial and institutional buildings [5]. The first system (a) has been historically present in Colombian architecture and is based on an inexpensive Guadua structural wall framing system with a plastered finish known in Spanish as 'bahareque encementado' (plastered cane). In response to the undervaluation of Guadua as a construction material, architects such as Oscar Hidalgo [6], Carlos Vergara and Simón Velez have pioneered a process for pushing the mechanical response of the material to its limit, producing full scale cantilevered roofs and long span structures.



Figure 4. Construction process of a Guadua building (a) Framing (b) Walling (c) Finishing

Figures 4a, b and c show the construction process for a building that combines systems (a) & (b) in a three storey holiday house in Colombia.

Following the regulations of the Colombian building code [5] practitioners, engineers and architects, including the first author, have participated in the construction of pedestrian bridges, large scale commercial and institutional buildings, urban dwellings and holiday homes. An example of a lightweight Guadua structure that follows these regulations is presented as a case study in this paper. Despite being designed as a framed structure with columns and beams, it also uses non-structural plastered cane for some walls.

Case study location

Project Bohio was built in Colombia in a river valley between the Central and Eastern ranges of the Andes mountain system close to Villeta, a town 80 km away from Bogotá D.C. Colombia is located on the extreme northwest of South America, on the border with Panamá and adjacent to the Atlantic and Pacific oceans (Figure 5a). This geographical situation, together with its position near the Equator provides Colombia with a tropical climate. Bohio is located at an altitude of about 900 m.a.s.l. and its average temperature is 25°C.

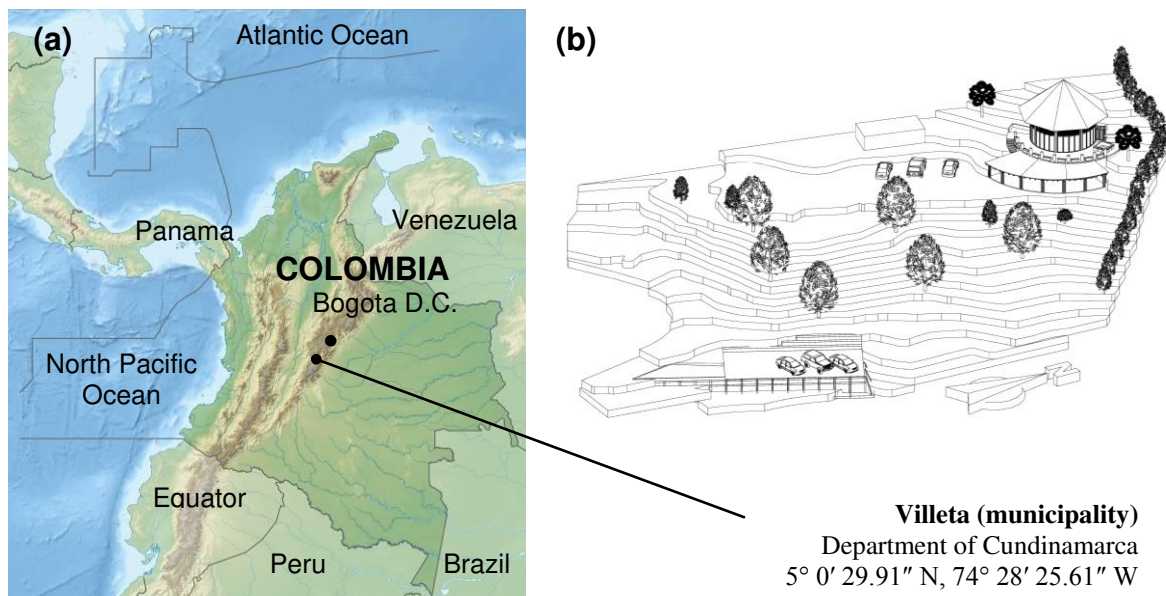


Figure 5 (a) Bohio's geographical location (b) Bohio's situation on the terrain.

The zone where the Bohio project was developed is located on a geological fault considered to be a medium earthquake risk within the Colombian building code [5] due to constant telluric and volcanic activity in the Pacific Ocean along the Ring of Fire.

Architectural Design

The design process for Bohio follows three main requirements from the owner:

- to conceive a bungalow type holiday house that utilizes only local and natural materials reducing environmental impact
- to avoid an urban style of appearance
- to integrate the building with the surrounding tropical landscape.

These requirements were achieved by evoking a vernacular style of architecture found in Colombia. Basic social, traditional and cultural concepts were integrated into the design which interacts with the environment by the intensive use of natural materials. As a result, a strong sense of appropriateness and architectural identity was attained. The project was implanted high on the side of a valley to gain the views over a river canyon (Figure 5b).

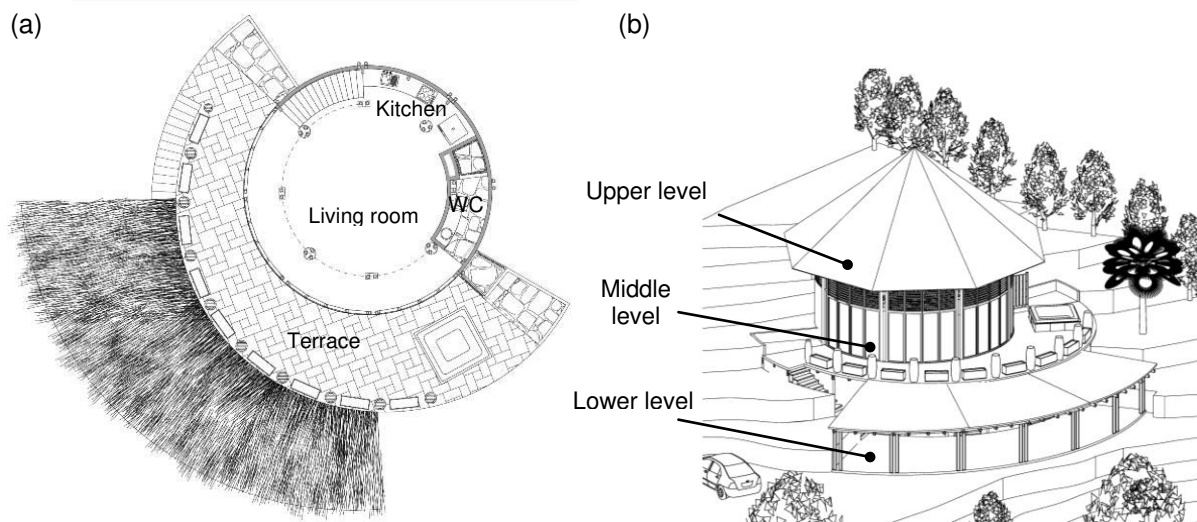


Figure 6. (a) Principal floor plan of Bohio. (b) Three dimensional view of Bohio.

As shown in Figure 6 a & b, this sloping plot allowed a three-level arrangement of the building to be constructed which resulted in separation into three functional zones: a private suite at the top level, a social area in the middle and an auxiliary accommodation and services area on the bottom floor. The middle zone contains an open kitchen and the living room which can be extended to the front terrace and serves as a transition to the lower level where guest, laundry and storage rooms are located. This distribution resembles the spatial hierarchy found in vernacular buildings where the building core contains the main zones (private and social) and auxiliary rooms are located in an external concentric zone.

A conical roof covers the two-storey circular superstructure while the lower level is covered by the projection of the ground floor slab over the basement, making room for an ample terrace and three separate rooms underneath (two for guests and one for storage and laundry). Adjacent to these rooms a sheltered terrace provides protection from the incident sun throughout the year and generates a fresh corridor ideal for hanging hammocks and setting up terrace tables.

The low profile of the basement (2.40m) contrasts with the tall superstructure (8.00m) but both are balanced by their size in the horizontal plane. Extended zones of shadow and generous openings for lighting and ventilation were key factors for assuring internal comfort levels. The thermal mass of the materials used in the building decreases from bottom to top where due to the hot humid climate, high density and high specific heat capacities are not needed.

Materials

As usual in bamboo construction the substructure is made out of concrete, isolating the bottom part of the bamboo superstructure from the soil and high moisture levels. In Bohio's case the structure above ground is completely built out of Guadua and composed of structural frames connected by steel bolts to the floors and roof and using diagonal components to concentrate the loads on the vertical load-bearing elements.

Bamboo-Guadua was selected as the mainstream structural material and comprises about 70% of the whole building. Timber is used for flooring, straw for the roof, fired bricks for the external walls and reinforced concrete for foundation and slabs. Between the 4th and 6th year when maturity is reached, Guadua is harvested for construction purposes. Its culms are subject to a preparation process before use which includes curing on stand for 20 days, preservation by an open tank method [7] for 5 days in a 5% solution of boric acid in water and commonly air dried to balance its moisture content with the construction environment to a maximum value of 19% [5].

Structural design

Bohio' structure (Figure 7) can be divided into three parts: the basement (substructure), the superstructure and the roof.

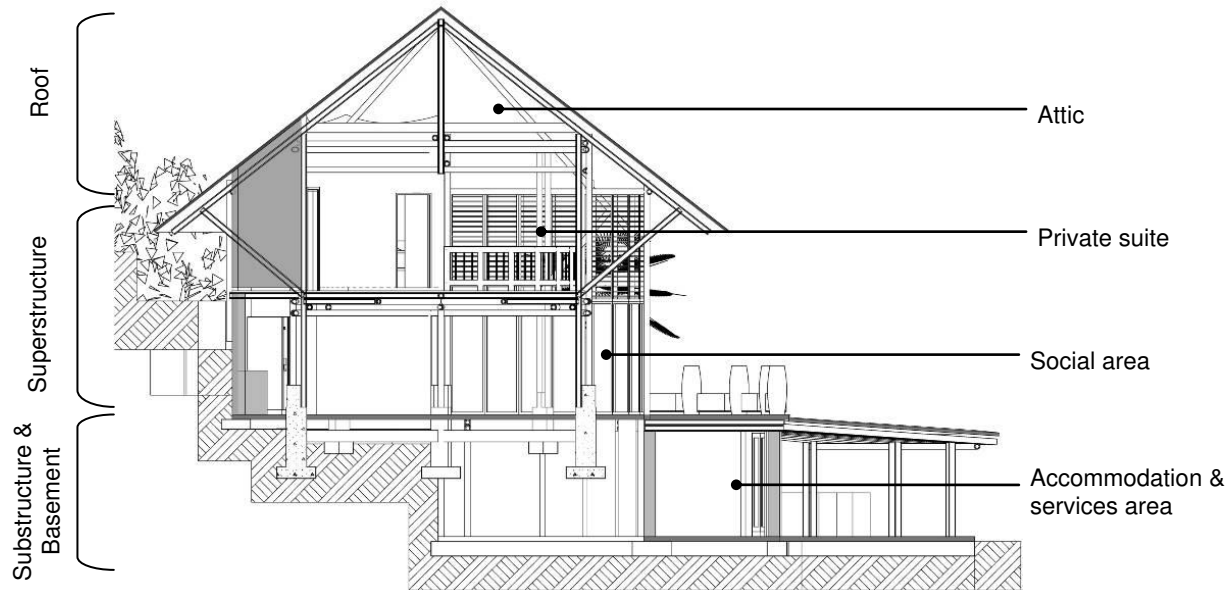


Figure 7. Bohio's structural and functional zones.

The basement is basically a solid box with a continuous retaining wall which contains the abutting ground. Its base is made out of reinforced concrete, and its walls of fired clay bricks strengthened with concrete piles to restrain lateral deflections. The foundation of the superstructure (Figure 8) consists of four main and four secondary concrete isolated footings interconnected by ground concrete beams. Three-flanged reinforced concrete pedestals emerge above ground from these footings to connect with three Guadua columns using bolts.



Figure 8. Superstructure of Bohio project. Smaller images show (top) the floor, (middle) roof and (bottom) three-flanged reinforced concrete pedestals.

Four bamboo columns composed of three elements set the edges of the main square frame and there are four additional two-component Guadua columns which define a secondary square which sits within the primary square but rotated by 45°. Each edge of the squares is connected by Guadua beams forming an octagon in the first and second levels of the structure. A radial arrangement of bamboo joists supports the timber decking of the first floor, while the roofing system lies on the top of the superstructure. An exterior frame system holds the facade and gives some extra support to the roof. The roof joist converges to the centre from the eight sided structure beneath, reaching a height of 8.00m above the ground floor.

Mechanical considerations

In general, the design of a bamboo building is considered as a semi-rigid system for structural purposes. Following the NSR-10 regulations, the allowable stresses for Guadua with a moisture content of 12 % in bending, tension, compression parallel to the grain, compression perpendicular to the grain and shear were 15, 18, 14, 1.4 and 1.2 MPa respectively. MOE ($E_{0.5}$) average was considered to be 9,500 MPa at the same moisture content. Live loads for this project were calculated to be 180 kg/m² and dead load of the roof to be 80 kg/m². Located in zone 2, as defined by NSR-10, wind loads were estimated at 22m/s = 80km/h. The values for seismic loads for the location of the project are $A_a=0.15$, $A_e=0.17$, $A_v=0.20$, $A_d=0.06$.

Foundations

Built out of reinforced concrete, the foundation soil beneath is prepared by laying down bedrock and concrete where the 1.00 x 1.00 m footings are cast. Square piles of 0.40 x 0.40 m axially emerge from the footings and form the three-flanged concrete pedestals that are connected to and support the Guadua structure. Horizontal holes are left during casting to fix the bolts that attach the columns of Guadua, and steel bars rise from the footings and emerge from the pedestal by 1m to allow continuity of load bearing. In order to attach steel bars to the ends of the Guadua columns one internode cavity is filled with mortar and the bars are bonded into the mortar.

Joints

Structural elements in construction with Guadua are fastened together with 3/8 inch bolts. These transverse bolted connections are located close to or through the nodes, however, due to the dimensional irregularity of the material it cannot be guaranteed. The hollow internodes are filled with cement mortar (10 MPa) to restrict displacement parallel to the grain and prevent crushing. To accommodate the bolts ½ inch holes are drilled into the Guadua. A rubber washer is located beneath the steel washer and nut. Nails and screws are used as non-structural fasteners.

Roof

The main components of the roof cladding (Figure 9a) are a corrugated steel sheet sandwiched between straw bunches with and a polyethylene membrane between the steel sheet and the inner layer of straw. Support is provided by Guadua-roof joists that converge in the centre of the conic roof. Parallel Moso bamboo roof battens arranged in the horizontal plan along the eight triangular sections of the roof tie together the straw bunches. The space left underneath by the 45 degree inclination of the roof gives room for an attic which is subdivided into a two-storey triangular set of bunks.

Installations

The piped water supply is centralized and mainly lies underground. At the superstructure level the two bathrooms are vertically overlapped which facilitates the concealment of the pipes conducting of the

water supply. Sewage water conducted by similarly concealed pipes is treated in-situ in a septic tank by an anaerobic process.

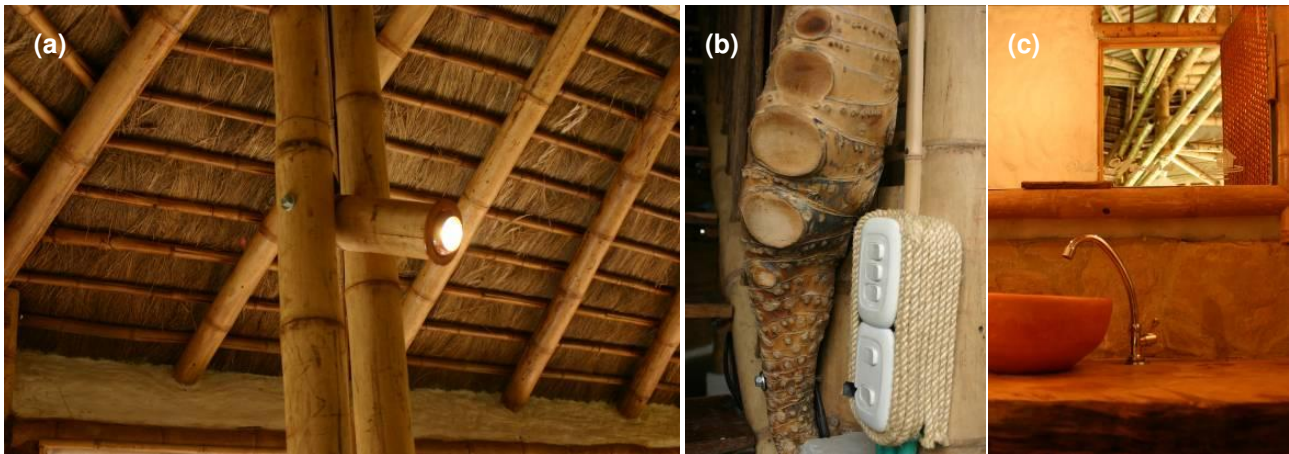


Figure 9. Architectural details of Bohio's Project (a) Ceiling (b) Installations (c) finishing details

The electric installations are spread across the building with rubber flexible cable (3 x 12 AWG). The absence of cladding leads to aesthetic issues due to the difficulties of embedding cable inside the Guadua or hiding it in a skeleton-like structure. Where possible cable was covered by half bamboo canes as shown in Figure 9b.

Internal features (Finishing)

Figures 9b & c show internal features where the design and selection of materials follow Bohio's architectural concept. Clay fired accessories for bathroom basins (Figure 9c), a wooden staircase, fitted furniture and gas lamps were inspired by vernacular architecture and regional traditions. Rattan fibres are specified for door faces and bed headboard, sisal cords for covering exposed installation pipes. The completed building is presented in Figure 10.



Figure 10. Bohio's project, external view.

Discussion

Currently, Guadua construction is characterized by a degree of uncertainty and depends on the quality of handicraft. A bamboo building can be designed in detail according to standards and construction codes which give guidelines for structural design and the selection of materials. However, during the construction process the natural variability of the material requires experienced craftsmen to deal with the different diameters, internode lengths and the tapering characteristic of bamboo. Also, expertise in carpentry is required for making cuts and connections. Verticality and horizontality are not easy to achieve. For instance, window frames were built out of Guadua in the uppermost level of Bohio to achieve some weather protection by design, but factors such as variability, the presence of nodes, the constant swelling and contraction and the round surface of the material, hindered the construction process and presented functionality issues. The bio-deterioration of the material presents another challenge for the protection of external building elements, such as columns, cladding or railings. Open porous coatings must be used and exhaustive maintenance performed every 4 to 6 months. Another demanding issue to consider in construction with Guadua is the arrangement of internal installations which cannot be hidden inside the culms and are usually exposed, leading to aesthetic and functional conflicts.

Conclusions

Project Bohio is an exemplary building constructed with bamboo *Guadua Angustifolia* Kunth that complies with the regulations of the Colombian building code for the design of Guadua structures. However, this standardized building system is relatively new and challenges such as the handicraft building process, the bio-deterioration of the material and its integration within conventional systems must be revised. Assessments of buildings such as the one presented in this paper are needed to evaluate the pros and cons of this building system. Once all the aspects have been thoroughly evaluated and environmental impacts addressed, a low carbon construction system using Guadua bamboo will be achieved.

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